



## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification<sup>7</sup> :

H01M 8/04

A1

(11) International Publication Number:

WO 00/16425

(43) International Publication Date:

23 March 2000 (23:03.00)

(21) International Application Number: PCT/CA99/00823

(22) International Filing Date: 14 September 1999 (14.09.99)

(30) Priority Data:

60/100,091	14 September 1998 (14.09.98)	US
2,274,240	10 June 1999 (10.06.99)	CA

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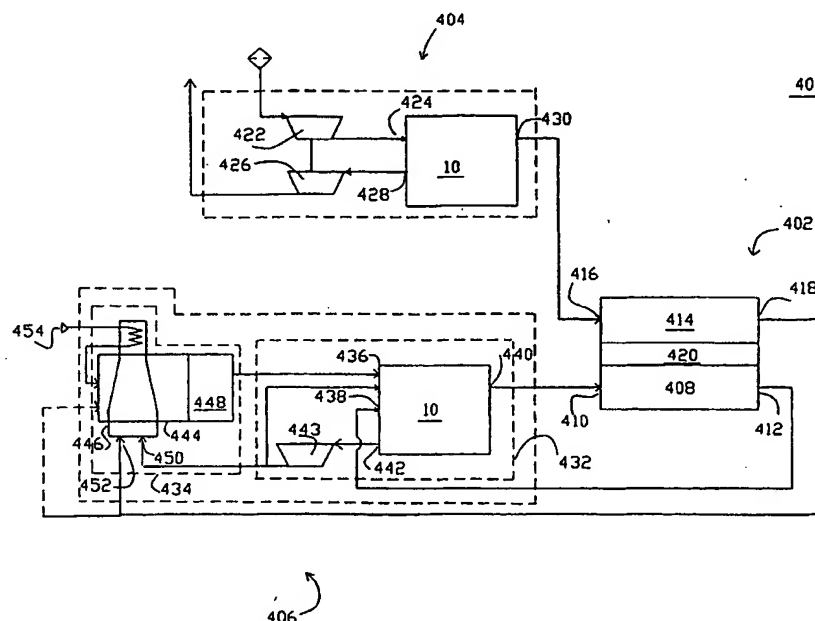
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published

With international search report.

Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: ELECTRICAL CURRENT GENERATION SYSTEM



(57) Abstract

An electrical current generating system consists of a fuel cell, and an oxygen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet for receiving a supply of hydrogen gas, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The electrical current generating system also includes gas recirculation means coupled to the cathode gas outlet for recirculating a portion of cathode exhaust gas exhausted from the cathode gas outlet to the cathode gas inlet.

## ELECTRICAL CURRENT GENERATION SYSTEM

## FIELD OF THE INVENTION

The present invention relates to a fuel cell for the generation of electrical current. In particular, the present invention relates to a fuel cell-based electrical generation system which employs pressure swing adsorption for enhancing the efficiency of the fuel cell.

## BACKGROUND OF THE INVENTION

Fuel cells provide an environmentally friendly source of electrical current. One form of fuel cell used for generating electrical power includes an anode for receiving hydrogen gas, a cathode for receiving oxygen gas, and an alkaline electrolyte. Another form of fuel cell includes an anode channel for receiving a flow of hydrogen gas, a cathode channel for receiving a flow of oxygen gas, and a polymer electrolyte membrane (PEM) which separates the anode channel from the cathode channel. In both instances, oxygen gas which enters the cathode reacts with hydrogen ions which cross the electrolyte to generate a flow of electrons. Environmentally safe water vapour is also produced as a byproduct. However, several factors have limited the widespread use of fuel cells as power generation systems.

Firstly, in order to extract a continuous source of electrical power from the fuel cell, it is necessary to provide the fuel cell with a continuous source of oxygen and hydrogen gas. However, with atmospheric air as the direct source of oxygen to the cathode channel, performance of PEM fuel cells is severely impaired by the low partial pressure of oxygen and the concentration polarization of nitrogen, while alkaline fuel cells require a pretreatment purification system to remove carbon dioxide from the feed air. Further, as the average oxygen concentration in a cathode channel with atmospheric air feed is typically only about 15%, the size of the fuel cell must be undesirably large in order to provide sufficient power for industrial applications.

In order to achieve a partial pressure of oxygen through the cathode channel sufficient for the attainment of competitive current densities from a PEM fuel cell system, particularly for vehicular propulsion, it is necessary to compress the air feed to at least 3 atmospheres before the air feed is introduced to the cathode channel. As will be appreciated, the power input necessary to sufficiently compress the air feed reduces the overall efficiency of the fuel cell system. It has been proposed to use polymeric membranes to enrich the oxygen, but such membranes actually reduce the oxygen partial pressure and the reduction in total pressure more than offsets the

However, the conventional system for implementing pressure swing adsorption or vacuum pressure swing adsorption uses two or more stationary adsorbent beds in parallel, with directional valving at each end of each adsorbent bed to connect the beds in alternating sequence to pressure sources and sinks. This system is often difficult and expensive to implement due to the complexity of the valving required.

Further, the conventional PSA system makes inefficient use of applied energy, because feed gas pressurization is provided by a compressor whose delivery pressure is the highest pressure of the cycle. In PSA, energy expended in compressing the feed gas used for pressurization is then dissipated in throttling over valves over the instantaneous pressure difference between the adsorber and the high pressure supply. Similarly, in vacuum-PSA, where the lower pressure of the cycle is established by a vacuum pump exhausting gas at that pressure, energy is dissipated in throttling over valves during countercurrent blowdown of adsorbers whose pressure is being reduced. A further energy dissipation in both systems occurs in throttling of light reflux gas used for purge, equalization, cocurrent blowdown and product pressurization or backfill steps. These energy sinks reduce the overall efficiency of the fuel cell system.

Additionally, conventional PSA systems can generally only operate at relatively low cycle frequencies, necessitating the use of large adsorbent inventories. The consequent large size and weight of such PSA systems renders them unsuitable for vehicular fuel cell applications.

Accordingly, there remains a need for an efficient fuel cell-based electrical generation system which can produce sufficient power for industrial applications and which is suitable for vehicular applications.

#### SUMMARY OF THE INVENTION

According to the invention, there is provided a fuel cell-based electrical generation system which addresses the deficiencies of the prior art fuel cell electrical generation systems.

The electrical current generating system, according to a first embodiment of the present invention, comprises a fuel cell, and a oxygen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet for receiving a supply of hydrogen gas, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel.

gas outlet, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel.

5 The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The hydrogen gas delivery system includes a hydrogen gas inlet for receiving a first hydrogen gas feed from the anode gas outlet, and a hydrogen gas outlet coupled to the anode gas inlet for delivering hydrogen gas received from the first hydrogen gas feed to the anode channel with increased purity.

10 In a preferred implementation of the second embodiment, the oxygen gas separation system comprises an oxygen pressure swing adsorption system, and the hydrogen gas separation system comprises a reactor for producing a second hydrogen gas feed from hydrocarbon fuel, and a hydrogen pressure swing adsorption system coupled to the reactor for purifying hydrogen gas received from the first and second hydrogen gas feeds. Both pressure swing adsorption systems include a rotary module having a stator and a rotor rotatable relative to the stator. The rotor  
15 includes a number of flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component. The function compartments include a gas feed compartment and a heavy product compartment.

In one variation, the oxygen pressure swing adsorption system includes a compressor  
20 coupled to the gas feed compartment for delivering pressurized air to the gas feed compartment, and a vacuum pump coupled to the compressor for extracting nitrogen product gas from the heavy product compartment. The reactor comprises a steam reformer, including a burner, for producing syngas, and a water gas shift reactor coupled to the steam reformer for converting the syngas to the second hydrogen gas feed. The hydrogen pressure swing adsorption system  
25 includes a vacuum pump for delivering fuel gas from the heavy product compartment to the burner. The fuel gas is burned in the burner, and the heat generated therefrom is used to supply the endothermic heat of reaction necessary for the steam reformer reaction. The resulting syngas is delivered to the water gas shift reactor for removal of impurities, and then delivered as the second hydrogen gas feed to the hydrogen pressure swing adsorption system.

30 In another variation, the invention includes a burner for burning fuel. The reactor comprises an autothermal reformer for producing syngas, and a water gas shift reactor coupled to the autothermal reformer for converting the syngas to the second hydrogen gas feed. The compressor of the oxygen pressure swing adsorption system delivers pressurized air to the

Fig. 12 shows an electrical current generating system, according to a second embodiment of the present invention, including an oxygen-separating PSA system for supplying enriched oxygen to the fuel cell cathode channel, and a hydrogen-separating PSA system for supplying enriched hydrogen to the fuel cell anode channel, with the hydrogen-separating PSA system receiving feed gas from a steam reformer; and

Fig. 13 shows an electrical current generating system, according to a variation of the electrical current generating system shown in Fig. 12, but with the hydrogen-separating PSA system receiving feed gas from an autothermal reformer.

Fig. 14 shows an electrical current generating system with carbon dioxide removal and oxygen enrichment for an alkaline fuel cell, and with an oxygen accumulator.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

To aid in understanding the present invention, a pressure swing adsorption process and associated apparatus, suitable for use with the present invention, will be described first, with reference to Figs. 1 through 6. Thereafter, an oxygen-separating pressure swing adsorption system and a hydrogen-separating pressure swing adsorption system will be described with reference to Figs. 7 and 8 respectively. Two embodiments of the invention, together with variations thereon, will then be described commencing with Fig. 9.

#### Figs. 1, 2, 3 and 4

A rotary module 10 which is suitable for use as part of the present invention is shown in Figs. 1, 2, 3 and 4. The module includes a rotor 11 revolving about axis 12 in the direction shown by arrow 13 within stator 14. However, it should be understood that the invention is not limited to PSA systems having rotary modules. Rather other arrangements may be employed without departing from the scope of the invention. For instance, if desired, the present invention may be employed with multiple stationary adsorbent beds in parallel, with directional valving at each end of each adsorbent bed to connect the beds in alternating sequence to pressure sources and sinks. However, as will become apparent, the rotary module 10 is preferred since it provides highly desirable features of efficiency and compactness.

In general, the rotary module 10 may be configured for flow through the adsorber elements in the radial, axial or oblique conical directions relative to the rotor axis. For operation at high cycle frequency, radial flow has the advantage that the centripetal acceleration will lie parallel to the flow path for most favourable stabilization of buoyancy-driven free convection,

34 and first end 30, and between second aperture 35 and second end 32, of adsorber element 24.

As shown in Fig. 3, stator 14 is a pressure housing including an outer cylindrical shell or first valve stator 40 outside the annular rotor 11, and an inner cylindrical shell or second valve stator 41 inside the annular rotor 11. Outer shell 40 carries axially extending strip seals (e.g. 42 and 43) sealingly engaged with first valve surface 21, while inner shell 41 carries axially extending strip seals (e.g. 44 and 45) sealingly engaged with second valve surface 23. Preferably, the azimuthal sealing width of the strip seals is greater than the diameters or azimuthal widths of the first and second apertures 34 and 35 opening through the first and second valve surfaces.

10 A set of first compartments in the outer shell each open in an angular sector to the first valve surface, and each provide fluid communication between its angular sector of the first valve surface and a manifold external to the module. The angular sectors of the compartments are much wider than the angular separation of the adsorber elements. The first compartments are separated on the first sealing surface by the strip seals (e.g. 42). Proceeding clockwise in Fig. 15 3, in the direction of rotor rotation, a first feed pressurization compartment 46 communicates by conduit 47 to first feed pressurization manifold 48, which is maintained at a first intermediate feed pressure. Similarly, a second feed pressurization compartment 50 communicates to second feed pressurization manifold 51, which is maintained at a second intermediate feed pressure higher than the first intermediate feed pressure but less than the higher working pressure.

20 For greater generality, module 10 is shown with provision for sequential admission of two feed mixtures, the first feed gas having a lower concentration of the more readily adsorbed component relative to the second feed gas. First feed compartment 52 communicates to first feed manifold 53, which is maintained at substantially the higher working pressure. Likewise, second feed compartment 54 communicates to second feed manifold 55, which is maintained at 25 substantially the higher working pressure. A first countercurrent blowdown compartment 56 communicates to first countercurrent blowdown manifold 57, which is maintained at a first countercurrent blowdown intermediate pressure. A second countercurrent blowdown compartment 58 communicates to second countercurrent blowdown manifold 59, which is maintained at a second countercurrent blowdown intermediate pressure above the lower working 30 pressure. A heavy product compartment 60 communicates to heavy product exhaust manifold 61 which is maintained at substantially the lower working pressure. It will be noted that compartment 58 is bounded by strip seals 42 and 43, and similarly all the compartments are bounded and mutually isolated by strip seals.

pressurization pressure. Finally, a third light reflux pressurization compartment 86 communicates to a first light reflux return manifold 87, which supplies the first light reflux gas which has been expanded from approximately the higher pressure to a third light reflux pressurization pressure greater than the second light reflux pressurization pressure, and in this example less than the first feed pressurization pressure.

Additional details are shown in Fig. 4. Conduits 88 connect first compartment 60 to manifold 61, with multiple conduits providing for good axial flow distribution in compartment 60. Similarly, conduits 89 connect second compartment 80 to manifold 81. Stator 14 has base 90 with bearings 91 and 92. The annular rotor 11 is supported on end disc 93, whose shaft 94 is supported by bearings 91 and 92. Motor 95 is coupled to shaft 94 to drive rotor 11. The rotor could alternatively rotate as an annular drum, supported by rollers at several angular positions about its rim and also driven at its rim so that no shaft would be required. A rim drive could be provided by a ring gear attached to the rotor, or by a linear electromagnetic motor whose stator would engage an arc of the rim. Particularly for hydrogen separation applications, the rotor drive may be hermetically enclosed within the stator housing to eliminate hazards related to seal leakage. Outer circumferential seals 96 seal the ends of outer strip seals 42 and the edges of first valve surface 21, while inner circumferential seals 97 seal the ends of inner strip seals 44 and the edges of second valve surface 23. Rotor 11 has access plug 98 between outer wall 20 and inner wall 22, which provides access for installation and removal of the adsorbent in adsorbers 24.

#### Figs. 5 and 6

Fig. 5 shows a typical PSA cycle which would be obtained using the foregoing gas separation system, while Fig. 6 shows a similar PSA cycle with heavy reflux recompression of a portion of the first product gas to provide a second feed gas to the process.

In Figs. 5 and 6, the vertical axis 150 indicates the working pressure in the adsorbers and the pressures in the first and second compartments. Pressure drops due to flow within the adsorber elements are neglected. The higher and lower working pressures are respectively indicated by dotted lines 151 and 152. The lower working pressure may be nominally or approximately ambient atmospheric pressure, or may be a subatmospheric pressure established by vacuum pumping. The higher working pressure may typically be in the range of twice to four times the lower working pressure, based on the ratio of absolute pressures.

The horizontal axis 155 of Figs. 5 and 6 indicates time, with the PSA cycle period defined by the time interval between points 156 and 157. At times 156 and 157, the working pressure

means 174, and (c) fourth light reflux exit compartment 78, dropping the adsorber pressure to the third cocurrent blowdown pressure 175 while delivering light reflux gas to fourth light reflux pressure letdown means 176. Second aperture 35 is then closed for an interval, until the light reflux return steps following the countercurrent blowdown steps.

5           The light reflux pressure let-down means may be mechanical expanders or expansion stages for expansion energy recovery, or may be restrictor orifices or throttle valves for irreversible pressure let-down.

          Either when the second aperture is closed after the final light reflux exit step (as shown in Figs. 5 and 6), or earlier while light reflux exit steps are still underway, first aperture 34 is  
10           opened to first countercurrent blowdown compartment 56, dropping the adsorber pressure to the first countercurrent blowdown intermediate pressure 180 while releasing "heavy" gas (enriched in the more strongly adsorbed component) to first exhaust means 181. Then, first aperture 34 is opened to second countercurrent blowdown compartment 58, dropping the adsorber pressure to the first countercurrent blowdown intermediate pressure 182 while releasing heavy gas to  
15           second exhaust means 183. Finally reaching the lower working pressure, first aperture 34 is opened to heavy product compartment 60, dropping the adsorber pressure to the lower pressure 152 while releasing heavy gas to third exhaust means 184. Once the adsorber pressure has substantially reached the lower pressure while first aperture 34 is open to compartment 60, the second aperture 35 opens to purge compartment 80, which receives fourth light reflux gas from  
20           fourth light reflux pressure let-down means 176 in order to displace more heavy gas into first product compartment 60.

          In Fig. 5, the heavy gas from the first, second and third exhaust means is delivered as the heavy product 185. In Fig. 6, this gas is partly released as the heavy product 185, while the balance is redirected as "heavy reflux" 187 to the heavy reflux compressor as fourth feed supply  
25           means 167. Just as light reflux enables an approach to high purity of the less readily adsorbed ("light") component in the light product, heavy reflux enables an approach to high purity of the more readily adsorbed ("heavy") component in the heavy product so that high recovery of the less readily adsorbed ("light") product can be achieved.

          The adsorber is then repressurized by light reflux gas after the first and second apertures  
30           close to compartments 60 and 80. In succession, while the first aperture 34 remains closed at least initially, (a) the second aperture 35 is opened to first light reflux pressurization compartment 82 to raise the adsorber pressure to the first light reflux pressurization pressure 190 while receiving third light reflux gas from the third light reflux pressure letdown means 174, (b)



could be performed by equalization with atmosphere as an intermediate pressure of the cycle. Similarly, a stage of countercurrent blowdown could be performed by equalization with atmosphere as an intermediate pressure of the cycle.

5 Fig. 7

Fig. 7 is a simplified schematic of a PSA system for separating oxygen from air using nitrogen-selective zeolite adsorbents. The light product is concentrated oxygen, while the heavy product is nitrogen-enriched air usually vented as waste. The cycle lower pressure 152 is illustrated as nominally atmospheric pressure, although a vacuum pressure 152 could be used as will be illustrated in Fig. 8. Feed air is introduced through filter intake 200 to a feed compressor 201. The feed compressor includes compressor first stage 202, intercooler 203, compressor second stage 204, second intercooler 205, compressor third stage 206, third intercooler 207, and compressor fourth stage 208. The feed compressor 201 as described may be a four stage axial compressor with motor 209 as prime mover coupled by shaft 210. The intercoolers are optional. With reference to Fig. 5, the feed compressor first and second stages are the first feed supply means 160, delivering feed gas at the first intermediate feed pressure 161 via conduit 212 and water condensate separator 213 to first feed pressurization manifold 48. Feed compressor third stage 206 is the second feed supply means 162, delivering feed gas at the second intermediate feed pressure 163 via conduit 214 and water condensate separator 215 to second feed pressurization manifold 51. Feed compressor fourth stage 208 is the third feed supply means 165, delivering feed gas at the higher pressure 151 via conduit 216 and water condensate separator 217 to feed manifold 53. Light product oxygen flow is delivered from light product manifold 71 by conduit 218, maintained at substantially the higher pressure less frictional pressure drops.

25 The PSA system of Fig. 7 includes energy recovery expanders, including light reflux expander 220 (here including four stages) and countercurrent blowdown expander 221 (here including two stages), coupled to feed compressor 201 by shaft 222. The expander stages may be provided for example as radial inflow turbine stages, as full admission axial turbine stages with separate wheels, or as partial admission impulse turbine stages combined in a single wheel.

30 Light reflux gas from first light reflux exit manifold 73 flows at the higher pressure via conduit 224 and heater 225 to first light pressure letdown means 170 which here is first light reflux expander stage 226, and then flows at the third light reflux pressurization pressure 192 by conduit 227 to the first light reflux return manifold 87. Light reflux gas from second light reflux

adsorbers have a thermal gradient along the flow path, with higher temperature at their second end relative to the first end. This is an extension of the principle of "thermally coupled pressure swing adsorption" (TCPSA), introduced by Keefer in U.S. Patent No. 4,702,903. Adsorber rotor 11 then acts as a thermal rotary regenerator, as in regenerative gas turbine engines having a compressor 201 and an expander 220. Heat provided to the PSA process by heater 225 assists  
5 powering the process according to a regenerative thermodynamic power cycle, similar to advanced regenerative gas turbine engines approximately realizing the Ericsson thermodynamic cycle with intercooling on the compression side and interstage heating on the expansion side. In the instance of PSA applied to oxygen separation from air, the total light reflux flow is much  
10 less than the feed flow because of the strong bulk adsorption of nitrogen. Accordingly the power recoverable from the expanders is much less than the power required by the compressor, but will still contribute significantly to enhanced efficiency of oxygen production.

If high energy efficiency is not of highest importance, the light reflux expander stages and the countercurrent blowdown expander stages may be replaced by restrictor orifices or  
15 throttle valves for pressure letdown. The schematic of Fig. 7 shows a single shaft supporting the compressor stages, the countercurrent blowdown or exhaust expander stages, and the light reflux stages, as well as coupling the compressor to the prime mover. However, it should be understood that separate shafts and even separate prime movers may be used for the distinct compression and expansion stages within the scope of the present invention.

20

#### Fig. 8

Fig. 8 shows a vacuum-PSA system, also with heavy product reflux as could be used to achieve high recovery in hydrogen purification for a fuel cell power plant. The raw hydrogen may be provided in certain stationary applications from chemical process or petroleum refinery  
25 offgases. However, in most fuel cell applications, the raw hydrogen gas feed will be provided by processing of a hydrocarbon or carbonaceous fuel, e.g. by steam reforming of natural gas, or by autothermal reforming or partial oxidation of liquid fuels. Such hydrogen feed gases typically contain 30% to 74% hydrogen. Using typical adsorbents such as zeolites, carbon dioxide, carbon monoxide, nitrogen and hydrogen sulphide or other trace impurities will be much more readily  
30 adsorbed than hydrogen, so the purified hydrogen will be the light product delivered at the higher working pressure which may be only slightly less than the feed supply pressure, while the impurities will be concentrated as the heavy product and will be exhausted from the PSA process as "PSA tail gas" at the lower working pressure. This tail gas will be used as fuel gas for the fuel

similar to that shown in Fig. 7 as the basic building block. However, it should be understood that the invention is not limited to electrical current generating systems having rotary PSA modules. Rather other arrangements may be employed without departing from the scope of the invention.

In Fig. 9, the PSA system separates oxygen from air, using nitrogen-selective zeolite adsorbents, as previously described. The light product is concentrated oxygen, while the heavy product is nitrogen-enriched air usually vented as waste. The cycle lower pressure 152 is nominally atmospheric pressure, unless an optional vacuum pump is provided as in Fig. 8. Feed air is introduced through filter intake 200 to a feed compressor 201. The feed compressor includes compressor first stage 202, compressor second stage 204, compressor third stage 206, , and compressor fourth stage 208. The feed compressor 201 as described may be a four stage axial compressor with motor 209 as prime mover coupled by shaft 210. The compressor stages may be in series as shown, or alternatively in parallel. Intercoolers between compressor stages are optional. The feed compressor first and second stages deliver feed gas at the first intermediate feed pressure 161 via conduit 212 and water condensate separator 213 to first feed pressurization manifold 48. Feed compressor third stage 206 delivers feed gas at the second intermediate feed pressure 163 via conduit 214 and water condensate separator 215 to second feed pressurization manifold 51. Feed compressor fourth stage 208 delivers feed gas at the higher pressure 151 via conduit 216 and water condensate separator 217 to feed manifold 53. Light product oxygen flow is delivered from light product manifold 71 by conduit 218, maintained at substantially the higher pressure less frictional pressure drops.

The apparatus of Fig. 9 includes energy recovery expanders, including light reflux expander 220 (here including four stages) and countercurrent blowdown expander 221 (here including two stages). Expander 221 is coupled to feed compressor 201 by shaft 222. The expander stages may be provided for example as radial inflow turbine stages, as full admission axial turbine stages with separate wheels, or as partial admission turbine stages combined in a single wheel. If high energy efficiency were not of highest importance, the light reflux expander stages and/or the countercurrent blowdown expander stages could be replaced by restrictor orifices or throttle valves for pressure letdown.

Light reflux gas from first light reflux exit manifold 73 flows at the higher pressure via conduit 224 and heater 225 to first light reflux expander stage 226, and then flows at the third light reflux pressurization pressure 192 by conduit 227 to the first light reflux return manifold 87. Light reflux gas from second light reflux exit manifold 75 flows at the first cocurrent blowdown pressure 171 via conduit 228 and heater 225 to the second expander stage 230, and

While higher temperature of the adsorbent will reduce nitrogen uptake and selectivity for each zeolite adsorbent, the isotherms will be more linear and humidity rejection will be easier: Working with adsorbents such as Ca-X and Li-X, recent conventional practice has been to operate ambient temperature PSA at subatmospheric lower pressures in so-called "vacuum swing adsorption" (VSA), so that the highly selective adsorbents operate well below saturation in  
5 nitrogen uptake, and have a large working capacity in a relatively linear isotherm range. At higher temperatures, saturation in nitrogen uptake is shifted to more elevated pressures, so the optimum PSA cycle higher and lower pressures are also shifted upward.

The enriched oxygen product gas is delivered by conduit 218, non-return valve 250, and  
10 conduit 251 to the inlet of oxygen product compressor 252 which boosts the pressure of product oxygen delivered by conduit 253. Compressor 252 may be a single stage centrifugal compressor, driven directly through shaft 254 by light reflux expander 220 or alternatively by a motor. Light reflux expander 220 may be the sole power source to compressor 252, in which case expander  
15 220 and compressor 252 together constitute a free rotor turbo-booster 255. Since the working fluid in both expander 220 and compressor 252 is enriched oxygen, the free rotor turbo-booster embodiment has the important safety feature of not requiring a shaft seal to an external motor. Preferably, energy recovered from light reflux expansion is used to raise the delivery pressure of the light product, here oxygen.

The compressed enriched oxygen is delivered to a fuel cell 260, by conduit 253 to  
20 cathode inlet 261 of fuel cell cathode channel 262. Fuel cell 260 may be of the polymer electrolyte membrane (PEM), with the electrolyte 265 separating cathode channel 262 from anode channel 266. Hydrogen fuel is supplied to anode inlet 267 of anode channel 266 by hydrogen infeed conduit 268.

The enriched oxygen passes through cathode channel 262 to cathode exit 270, as a  
25 fraction of the oxygen reacts with hydrogen ions crossing the membrane to generate electrical power and reacting to form byproduct water. The cathode exit gas leaving the cathode channel in conduit 280 from cathode exit 270 (in this preferred embodiment) is still significantly enriched in oxygen relative to ambient air concentration of approximately 21%. A minor portion of this gas is purged as cathode purge gas from conduit 280 by purge valve 285 and purge exhaust 286,  
30 and the balance of the cathode exit gas is retained as cathode recycle gas. The cathode recycle gas is conveyed by conduit 281 to water condensate separator 282 where excess liquid water is removed from the cathode exit gas, which remains saturated in water vapour. The humid cathode recycle gas is then blended with incoming enriched oxygen from the PSA system by conduit 283

countercurrent blowdown expander 221 to feed compressor 201 has been removed. Instead, vacuum pump 301 is used to depress the low pressure of the cycle below atmospheric pressure; drawing nitrogen-enriched waste gas from heavy product exhaust compartment 61 via conduit 246 and optional heater 302. Pump 301 is powered by countercurrent blowdown expander 304 expanding countercurrent blowdown gas from first countercurrent blowdown manifold 57 via conduit 240 and optional heater 241. Vacuum pump 301 and expander 304 are coupled by shaft 305, and together constitute a free rotor vacuum pump assembly 306. Such a free rotor vacuum pump offers attractive advantages of efficiency and capital cost. Alternatively, a motor could be coupled to an extension of shaft 305.

10           The countercurrent blowdown gas from second countercurrent blowdown manifold 59 exits that manifold at a pressure which is substantially atmospheric or slightly greater according to the amount of throttling restriction associated with conduit 244.

#### Fig. 11

15           Fig. 11 shows a fuel cell-based electrical current generating system, similar to the electrical current generating system of Fig. 9, but without light reflux energy recovery, and with a portion of oxygen enriched gas discharged from the fuel cell cathode being used for a pressurization step. The illustrative four stages of light reflux pressure letdown are achieved irreversibly over adjustable orifices 350, 351, 352 and 353 which respectively connect conduits 20   224 and 227, 228 and 231, 232 and 235, and 236 and 239. Orifices 350, 351, 352 and 353 are actuated through linkage 354 by actuator(s) 355. Adjustment of the orifices is desirable to enable turndown of the PSA apparatus to operation at reduced cycle frequency and reduced flow rates when the fuel cell power plant is operated at part load.

          The fuel cell has a cathode recycle loop defined (in the loop flow direction) by water 25   condensate separator 360, conduit 361 conveying enriched oxygen to cathode channel inlet 261, cathode channel 262, conduit 362 conveying cathode exhaust gas from cathode channel exit 270 to cathode recycle conduit 365 including cathode recycle blower 363 to repressurize the cathode recycle gas for admission to condensate separator 360. Separator 360 removes fuel cell water exhaust condensate from the cathode recycle loop, while also humidifying the dry concentrated 30   oxygen admitted from the PSA system conduit from conduit 218.

          A portion of the cathode exhaust is removed from conduit 362 by conduit 371, branching from cathode recycle conduit 365. This portion of the cathode exhaust gas is recycled to the feed end of the PSA (or alternatively vacuum-PSA) apparatus, and is conveyed by conduit 371 to

the anode channel 408 and the cathode channel 414.

The oxygen-PSA system 404 extracts oxygen gas from feed air, and comprises a rotary module 10, and a compressor 422 for delivering pressurized feed air to the feed compartments 424 of the rotary module 10. Preferably, the oxygen-PSA system 404 includes a vacuum pump 426 (or alternatively countercurrent blowdown expander) coupled to the compressor 422 for withdrawing nitrogen-enriched gas as heavy product gas from the blowdown compartments 428 of the rotary module 10. The oxygen-PSA system 404 also includes a light product gas function compartment 430 coupled to the cathode gas inlet 416 for delivering oxygen-enriched gas to the cathode channel 414. Cathode recycle may be provided as in the embodiments of Figs. 9 - 11.

10       The hydrogen gas production system 406 comprises a hydrogen-generating PSA system 432, and a fuel processor reactor 434 coupled to the hydrogen-PSA system 432 for supplying a first hydrogen gas feed to the hydrogen-PSA system 432. The hydrogen-PSA system 432 comprises a rotary module 10 including a first feed gas compartment 436 for receiving a first hydrogen gas feed from the reactor 434, a pressurization compartment 438 for receiving a  
15       hydrogen gas feed from the anode gas outlet 412, a light product compartment 440 for delivering hydrogen gas to the anode gas inlet 410, and a blowdown compartment 441 for delivering tail gas as heavy product gas to the reactor 434. Preferably the hydrogen-PSA system 432 includes a vacuum pump 442 (or alternately a countercurrent blowdown expander) provided between the blowdown compartment 441 and the reactor 434 for extracting the tail gas from the blowdown  
20       compartment 441.

According to the purity level of the hydrogen gas recycled from the anode gas exit 412, pressurization compartment 438 may cooperate with either the first or second valve of the rotary module, the latter being preferred if the purity of this stream is relatively high. The hydrogen-PSA system 432 may also include a heavy reflux compressor 443 delivering heavy reflux gas  
25       to a second feed gas compartment 444 to improve the fractional recovery of hydrogen gas. The calorific fuel gas requirements of the hydrogen gas production system 406 will determine the correct recovery of hydrogen gas.

The reactor 434 comprises a steam reformer 445, including a burner 446 and catalyst tubes (not shown), and a water gas shift reactor 448. The burner 446 includes a first burner inlet  
30       450 for receiving the tail gas from the blowdown compartment 442, and a second burner inlet 452 for receiving air or humid oxygen-enriched gas from the cathode channel 414. The steam reformer 444 is supplied through a fuel inlet 454 with a hydrocarbon fuel, such as methane gas, plus water at a feed pressure which is the working pressure of the fuel cell plus an allowance for

The resulting gas reactants are then conveyed to the first feed compartment 436 of the hydrogen-PSA system 432 for hydrogen purification, with the heavy product tail gas being purged from the hydrogen-PSA system 432.

In another variation, the reactor 434 comprises an autothermal reformer and a water gas shift reactor 448, and instead of the methane gas mixture being endothermically steam reformed or exothermically partially oxidized, the methane gas mixture is reacted in the autothermal reformer by a thermally balanced combination of those reactions, followed by reaction in the water gas shift reactor 448. Since the hydrogen-PSA heavy product tail gas will always have some fuel value even in the limit of very high heavy reflux, a burner 446 would be provided for efficiently preheating air and or fuel feeds to an autothermal reactor. Unless the fuel processing reactions include an endothermic reforming component as an energy-efficient sink for tail gas fuel combustion, another economic use (as in the embodiment of Fig. 13) should be provided if the net fuel processing reactions are highly endothermic, as in the case of simple partial oxidation.

### Fig. 13

It will be apparent that a deficiency of the electrical current generating system 400 relates to the necessity of driving the compressor 422 and the vacuum pumps 426, 444 with a portion of the electrical power generated by the fuel cell. Fig. 13 shows a fuel-cell based electrical current generating system 500, which addresses this deficiency.

The electrical current generating system 500 is substantially similar to the electrical current generating system 400, comprising the fuel cell 402, an oxygen-generating PSA system 504, and a hydrogen gas production system 506. The oxygen-PSA system 504 extracts oxygen gas from feed air, and comprises a rotary module 10, a compressor 522 for delivering pressurized feed air to the feed compartments 524 of the rotary module 10, a combustion expander 523 coupled to the compressor 522, a starter motor (not shown) coupled to the compressor 522, and a light product gas function compartment 530 coupled to the cathode gas inlet 416 for delivering oxygen-enriched gas to the cathode channel 414. The oxygen-PSA system 504 may also have a countercurrent blowdown or heavy product exhaust compartment 531 cooperating with a vacuum pump and/or expander, as illustrated in previous embodiments.

The hydrogen gas production system 506 comprises a hydrogen-generating PSA system 532, and a reactor 534 coupled to the hydrogen-PSA system 532 for supplying a first hydrogen gas feed to the hydrogen-PSA system 532. The hydrogen-PSA system 532 comprises a rotary

crucial problem is removal of  $\text{CO}_2$  from both feed oxidant and hydrogen streams. The oxygen-PSA and hydrogen-PSA systems of this invention as described above will remove  $\text{CO}_2$  very effectively, since  $\text{CO}_2$  is much more strongly adsorbed than other permanent gas impurities. Oxygen enrichment is beneficial for all types of fuel cells in increasing voltage efficiency, although not usually justified except at high current densities. Alkaline fuel cells can use an under-sized oxygen-PSA for very effective carbon dioxide removal along with modest oxygen enrichment, or may use the same PSA device with an adsorbent lacking nitrogen/oxygen selectivity (e.g. activated carbon, or high silica zeolites) for carbon dioxide clean-up without oxygen enrichment. The rotary PSA module and compression machinery of this invention are entirely suitable for this role.

Alkaline fuel cells operating on ambient air feed typically operate near atmospheric pressure, at about  $70^\circ\text{C}$ . Under such conditions, the water vapour saturated cathode exhaust stream of nitrogen-enriched air serves to remove fuel cell product water while maintaining electrolyte water balance. Operation of alkaline fuel cells at higher temperature may be desirable for high efficiency with less costly electrocatalyst materials, or else for thermal integration to a methanol reformer using fuel cell waste heat to vapourize reactants and even drive the endothermic reaction. But with increasing stack exhaust temperatures, operation with ambient air composition may rapidly become impracticable. At higher temperatures, the nitrogen rich cathode exhaust simply carries too much water vapour out of the system, unless the total pressure is uneconomically raised or else a condenser for water recovery is included.

With oxygen enrichment, the volume of the cathode exhaust can be adjusted to achieve water balance for any alkaline fuel cell. Reasonable low stack working pressures become practicable, e.g. about 3 atmospheres for a cathode exit temperature of  $120^\circ\text{C}$ . If oxygen enrichment is carried out to the full capability of oxygen-PSA, e.g. approaching 95% oxygen purity, the cathode exhaust stream becomes dry steam with a modest concentration of permanent gases. This steam product may be useful for diverse applications, including fuel processing of hydrocarbon feedstocks to generate hydrogen.

Embodiment 600 shows an oxygen-PSA (also performing  $\text{CO}_2$  removal) as shown in Fig. 12. The hydrogen side of the system is simplified in this example to show only the anode gas inlet of pure hydrogen. Oxygen at more than 90% purity is supplied to the cathode gas inlet 416, while concentrated water vapour is delivered from cathode gas exit 418 and conveyed directly to steam expander 610. Expander 610 discharges to vacuum condenser 612, from which liquid condensate is removed by pump 614, while the permanent gas overheads are withdrawn



## WE CLAIM:

1. An electrical current generating system comprising:  
a fuel cell including an anode channel including an anode gas inlet for receiving a supply of hydrogen gas, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;  
an oxygen gas delivery system coupled to the cathode gas inlet for delivering oxygen gas to the cathode channel; and  
first gas recirculation means coupled to the cathode gas outlet for recirculating a first portion of cathode exhaust gas exhausted from the cathode channel to the cathode gas inlet.
2. The current generating system according to claim 1, wherein the first gas recirculating means comprises a compressor for supplying the first cathode exhaust gas portion under pressure to the cathode gas inlet.
3. The current generating system according to claim 2, wherein the first gas recirculation means includes a condensate separator coupled between the cathode gas outlet and the compressor for removing moisture from the first cathode exhaust gas portion.
4. The current generating system according to claim 1, wherein the oxygen gas delivery system comprises a gas separation system for extracting oxygen gas from air, the gas separation system including a first feed gas inlet for receiving an air feed, and an oxygen gas outlet coupled to the cathode gas inlet for supplying enriched oxygen gas to the cathode channel.
5. The current generating system according to claim 4, wherein the gas recirculating means directs the first cathode exhaust gas portion as feed gas to the gas separation system.
6. The current generating system according to claim 4, wherein the gas separation system includes a second feed gas inlet, and the current generating system includes second gas recirculating means coupled to the cathode gas outlet for recirculating a second portion of the cathode exhaust gas to the second feed gas inlet.

gas inlet.

13. The current generating system according to claim 12, wherein the pressure swing adsorption system includes a heater disposed between the light reflux exit compartment and the light reflux expander for enhancing recovery of energy from light reflux gas exhausted from the light reflux exit compartment.

14. The current generating system according to claim 12, wherein the function compartments include a gas feed compartment and a countercurrent blowdown compartment, and the compression machinery comprises a compressor coupled to the first feed gas inlet for delivering compressed air to the gas feed compartment, and an expander coupled to the compressor for exhausting heavy product gas enriched in the first gas component from the countercurrent blowdown compartment.

15. The current generating system according to claim 12, wherein the function compartments include a countercurrent blowdown compartment and a heavy product compartment, and the compression machinery comprises an expander coupled to the countercurrent blowdown compartment, and a vacuum pump coupled to the expander for extracting heavy product gas enriched in the first gas component at subatmospheric pressure from the heavy product compartment.

16. The current generating system according to claim 10, wherein the function compartments include a gas feed compartment, and the gas recirculating means directs the first cathode exhaust gas portion as feed gas to the gas feed compartment.

17. The current generating system according to claim 10, wherein the function compartments include a gas feed compartment, and the current generating system includes second gas recirculating means coupled to the cathode gas outlet for recirculating a second portion of the cathode exhaust gas to the gas feed compartment.

18. The current generating system according to claim 17, wherein the second gas recirculating means comprises a restrictor orifice.

received from the first and second hydrogen gas feeds.

25. The electrical current generating system according to claim 24, wherein the hydrogen gas separation system receives the first and second hydrogen gas feed, and produces the purified hydrogen therefrom.

26. The electrical current generating system according to claim 25, wherein the hydrogen gas separation system includes a first feed gas inlet for receiving the first hydrogen gas feed, and a second feed gas inlet for receiving the second hydrogen gas feed.

27. The electrical current generating system according to claim 26, wherein the first hydrogen gas feed is provided at a pressure level different from a pressure level of the second hydrogen gas feed.

28. The electrical current generating system according to claim 24, wherein the reactor comprises a steam reformer, and a water gas shift reactor coupled to the steam reformer for producing the second hydrogen gas feed.

29. The electrical current generating system according to claim 28, wherein the steam reformer includes a burner including a first burner inlet coupled to the cathode gas outlet for receiving humid oxygen-enriched gas, and a second burner inlet for receiving hydrogen gas from the hydrogen gas separation system for burning within the burner for providing endothermic heat of reaction for steam reforming of the hydrocarbon fuel.

30. The electrical current generating system according to claim 24, wherein the reactor comprises an autothermal reformer, and a water gas shift reactor coupled to the steam reformer for producing the second hydrogen gas feed.

31. The electrical current generating system according to claim 30, wherein the oxygen gas delivery system comprises an oxygen gas separation system for extracting oxygen gas from air, the gas separation system including a first feed gas inlet for receiving an air feed, and an oxygen gas outlet coupled to the cathode gas inlet for supplying the extracted oxygen gas to the cathode channel from the air feed, and the reactor comprises a burner including a first burner inlet for receiving air,

channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;

supplying hydrogen gas to the anode gas inlet;

supplying oxygen gas to the cathode gas inlet for reacting with the hydrogen gas;

recirculating a portion of cathode gas exhausted from the cathode gas outlet to the cathode gas inlet.

38. The method according to claim 37, wherein the recirculating step comprises delivering the exhaust gas portion at increased pressure to the cathode gas inlet.

39. The method according to claim 38, wherein the recirculating step further comprises purging a remainder of the exhaust gas.

40. The method according to claim 38, wherein the step of supplying oxygen gas comprises the steps of supplying an air feed to an oxygen pressure swing adsorption apparatus, and delivering oxygen-enriched gas extracted from the air feed as light product gas to the cathode gas inlet, and the recirculating step further comprises recovering waste heat from the fuel cell for enhancing recovery of expansion energy from the pressure swing adsorption apparatus.

41. The method according to claim 38, wherein the step of supplying oxygen gas comprises the steps of supplying an air feed to an oxygen pressure swing adsorption apparatus as a first gas feed, and delivering oxygen-enriched gas extracted from the first gas feed as light product gas to the cathode gas inlet, and the recirculating step further comprises delivering a remainder of the exhaust gas to the pressure swing adsorption apparatus as a second gas feed.

42. A method for generating electrical potential comprising the steps of:

providing a fuel cell including an anode channel including an anode gas inlet, a cathode channel including a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion exchange between the anode and cathode channel;

supplying hydrogen gas to the anode gas inlet;

supplying oxygen gas to the cathode gas inlet; and

and cathode channel;

an oxygen gas delivery system coupled to the cathode gas inlet for delivering enriched oxygen gas to the cathode channel, the oxygen gas delivery system including a pressure swing adsorption system to enrich oxygen and to remove carbon dioxide from atmospheric air feed; and

a hydrogen gas delivery system coupled to the anode gas inlet for delivering purified hydrogen gas to the cathode channel.

49. The current generating system according to claim 48, further including an oxygen accumulator interposed between the oxygen gas delivery system and the cathode gas inlet.

50. The current generating system according to claim 48, in which the electrolyte is alkaline and is maintained at a working temperature greater than about 100°C, the oxygen gas delivery system is operated to supply oxygen of about 90% purity to the cathode gas inlet, so that the product water of the fuel cell is delivered as concentrated dry steam from the cathode gas outlet; the system including a steam expander to expand the steam from the cathode gas outlet to a vacuum condenser, a condensate pump to exhaust liquid from the condenser, and a vacuum pump cooperating with the oxygen pressure swing adsorption system and exhausting permanent gas overheads from the vacuum condenser.

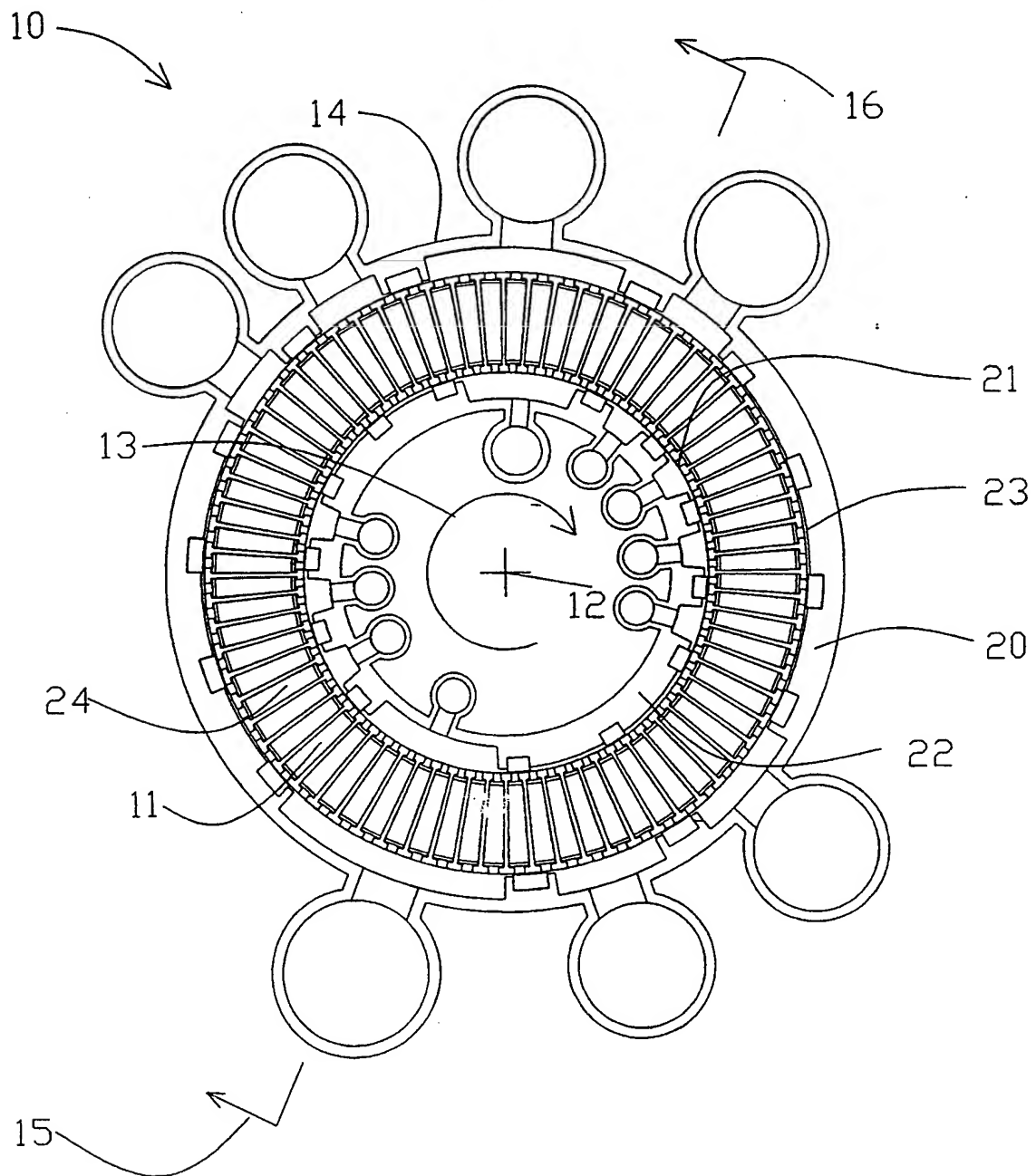


Fig. 1

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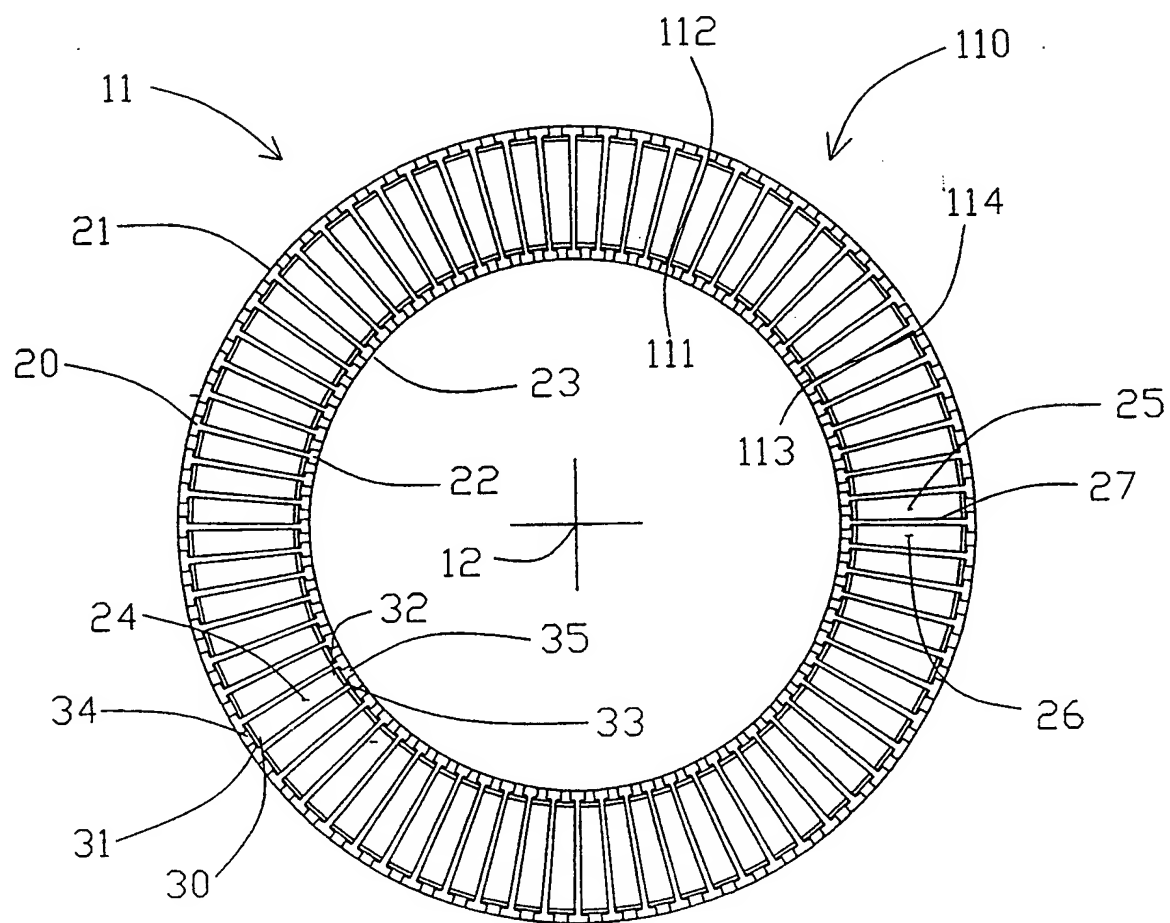


Fig. 2

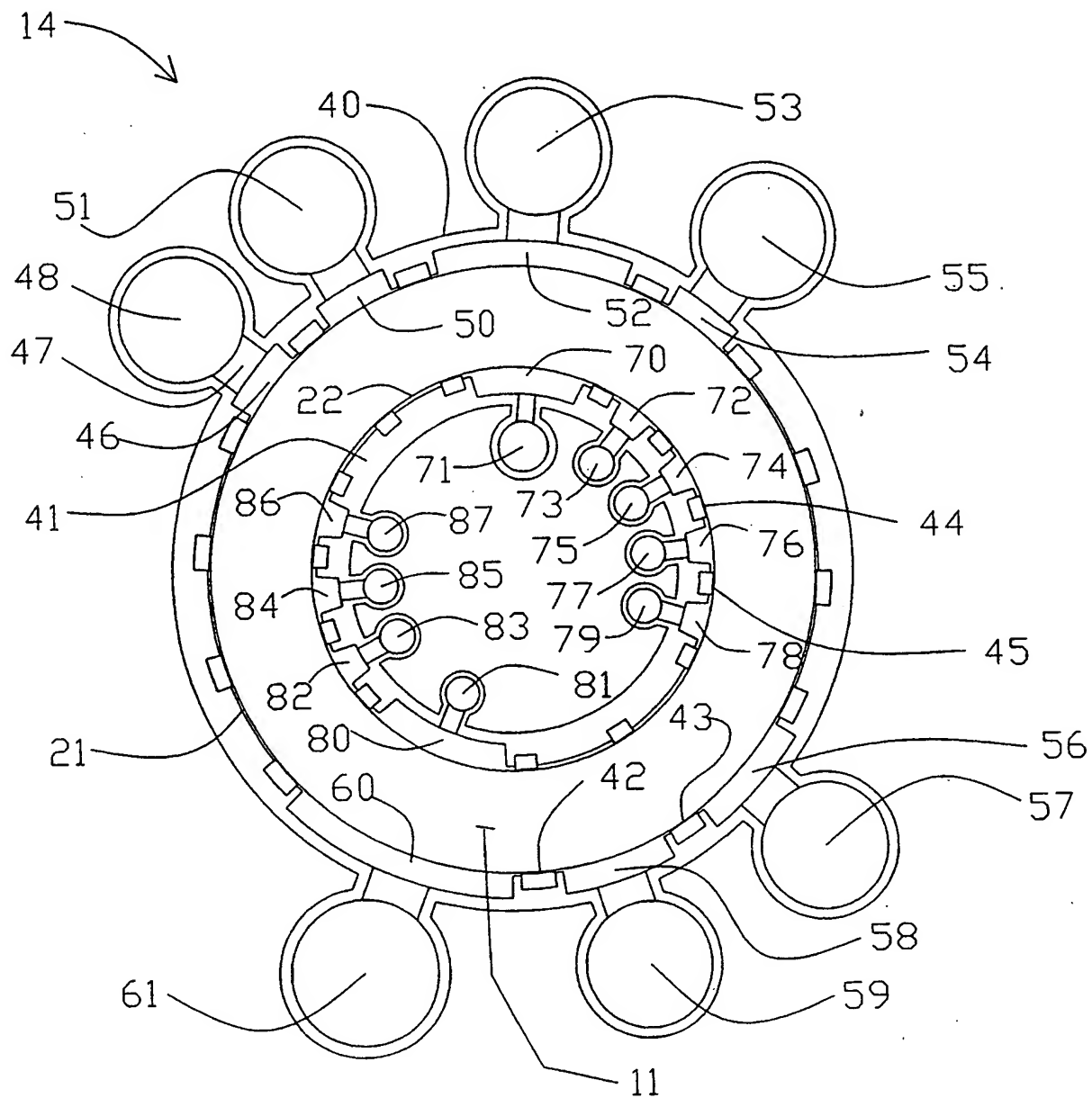


Fig. 3



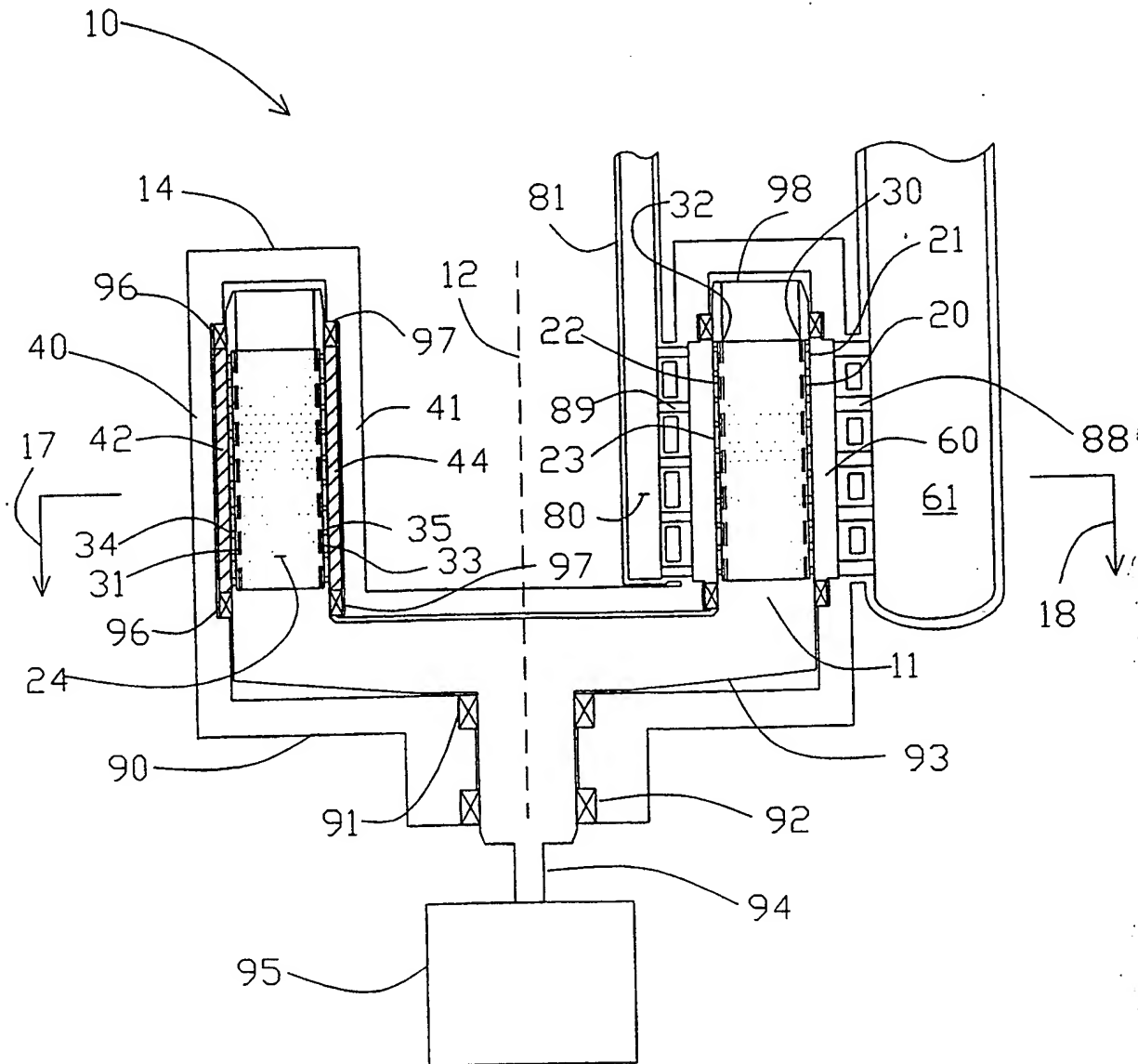


Fig. 4

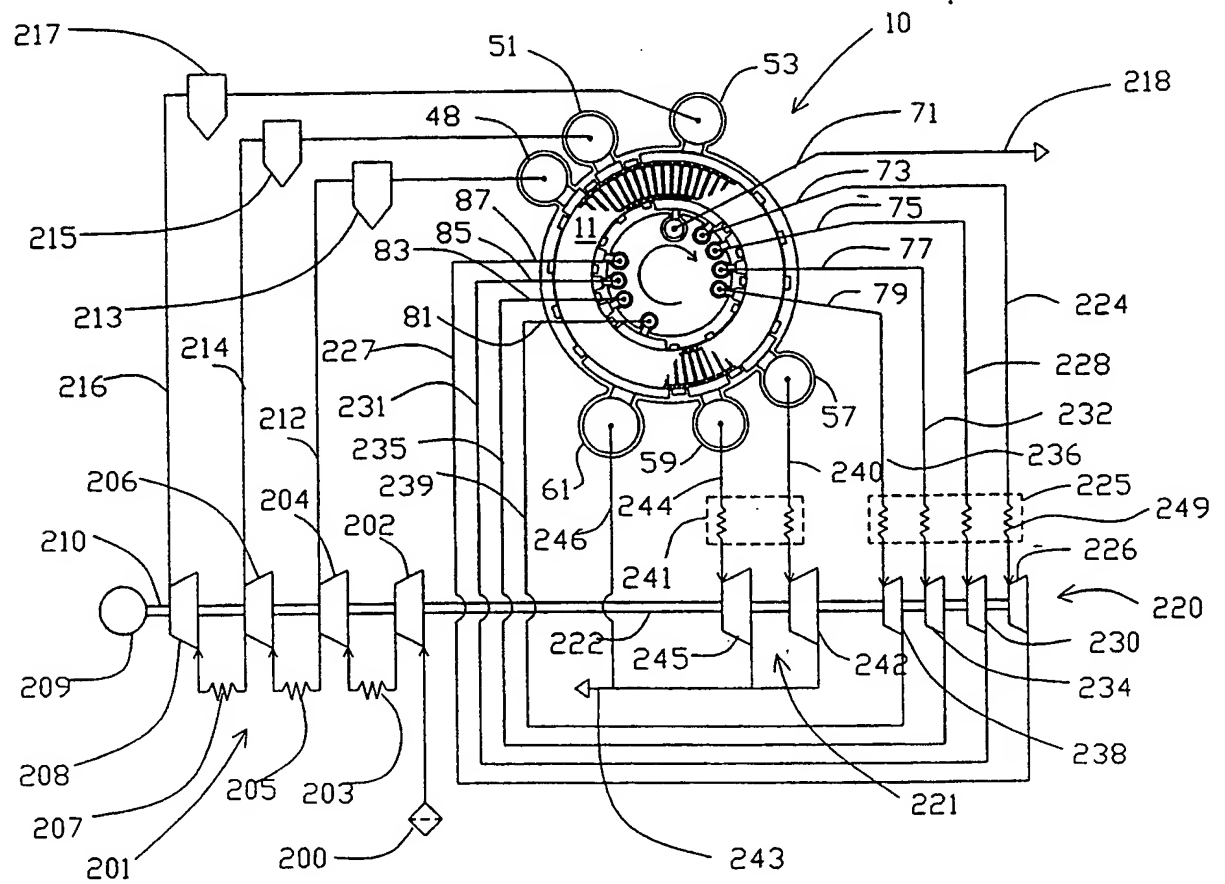
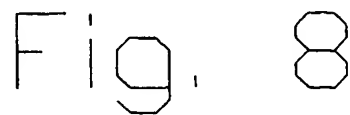


Fig. 7



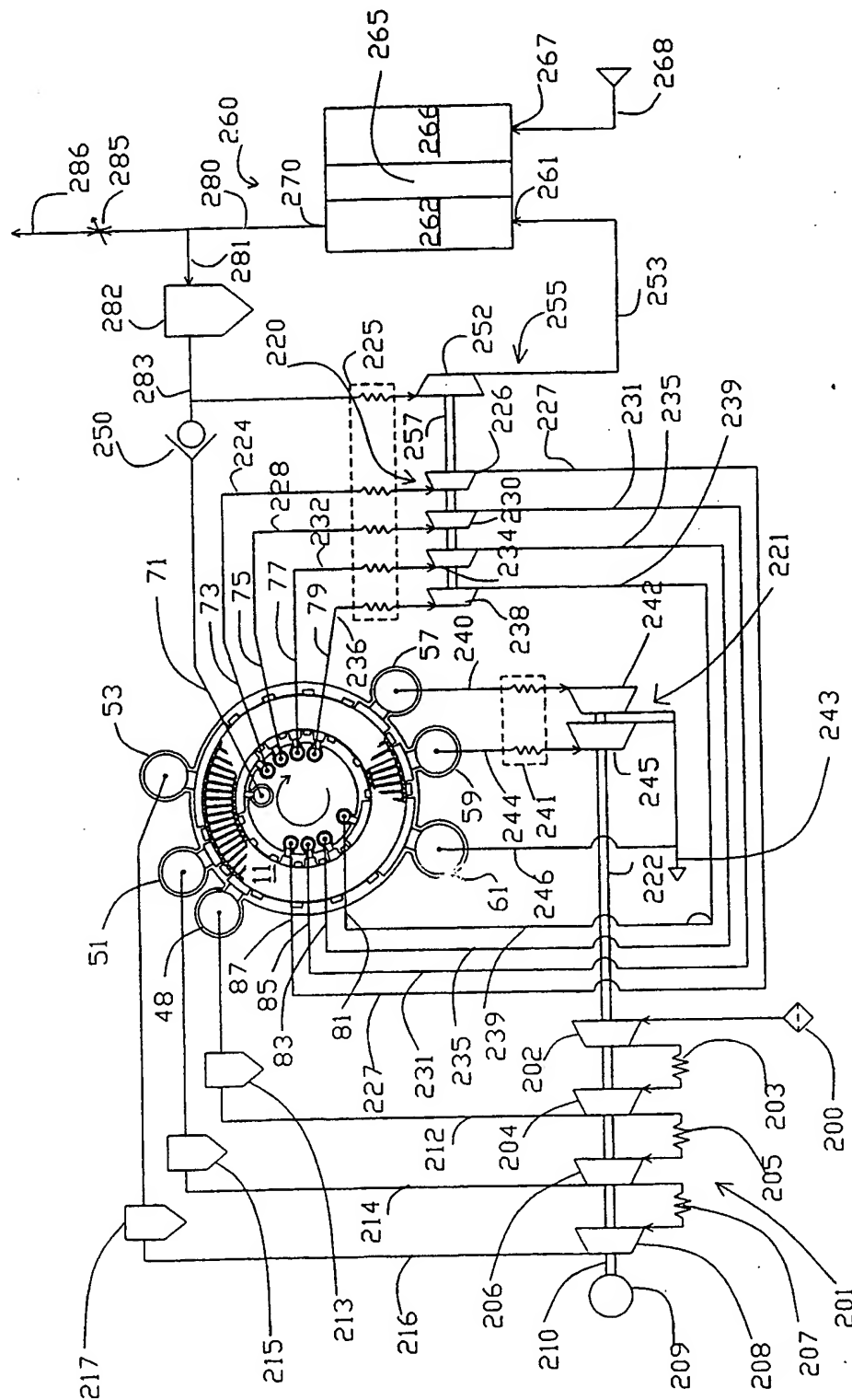


Fig. 9

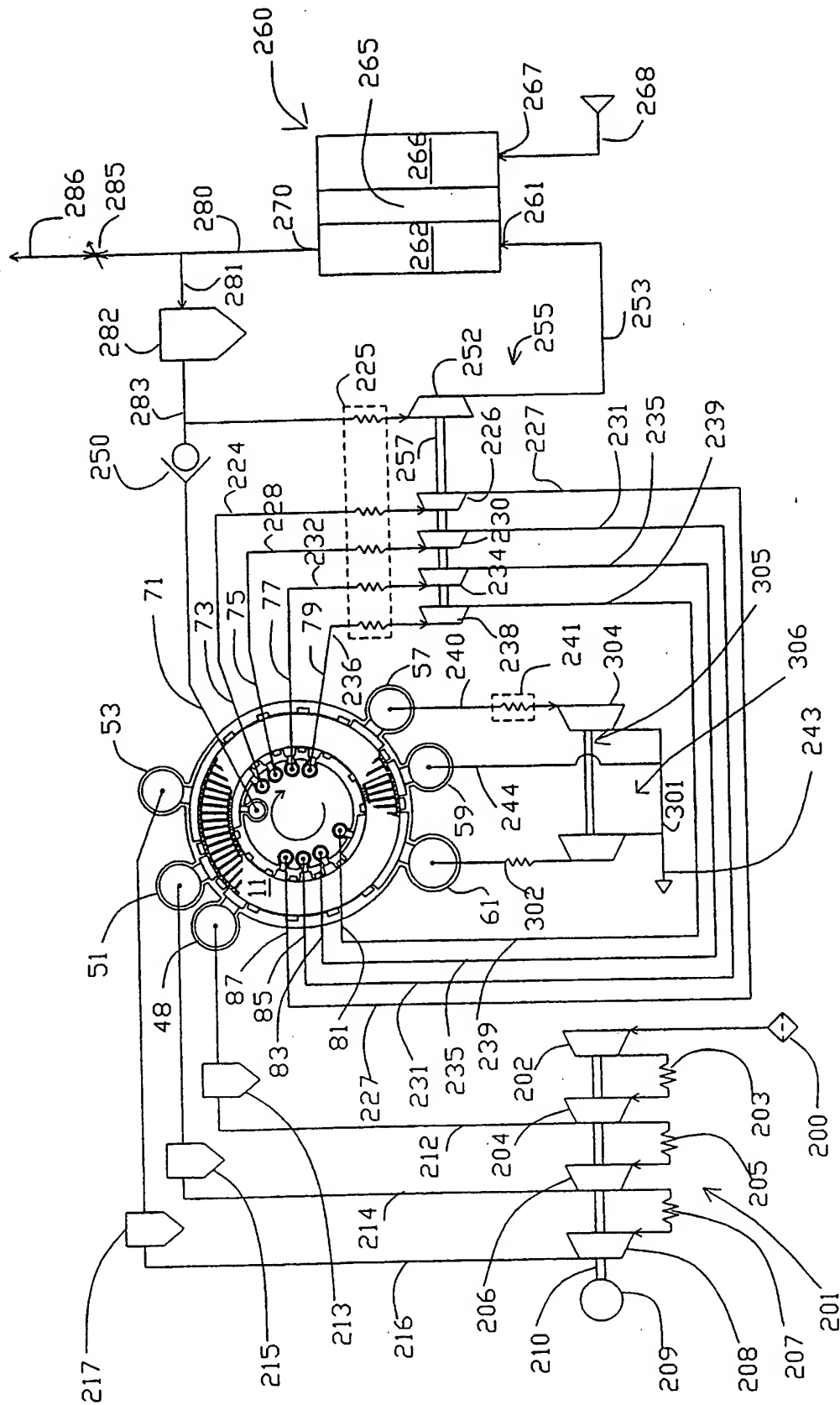


Fig. 10

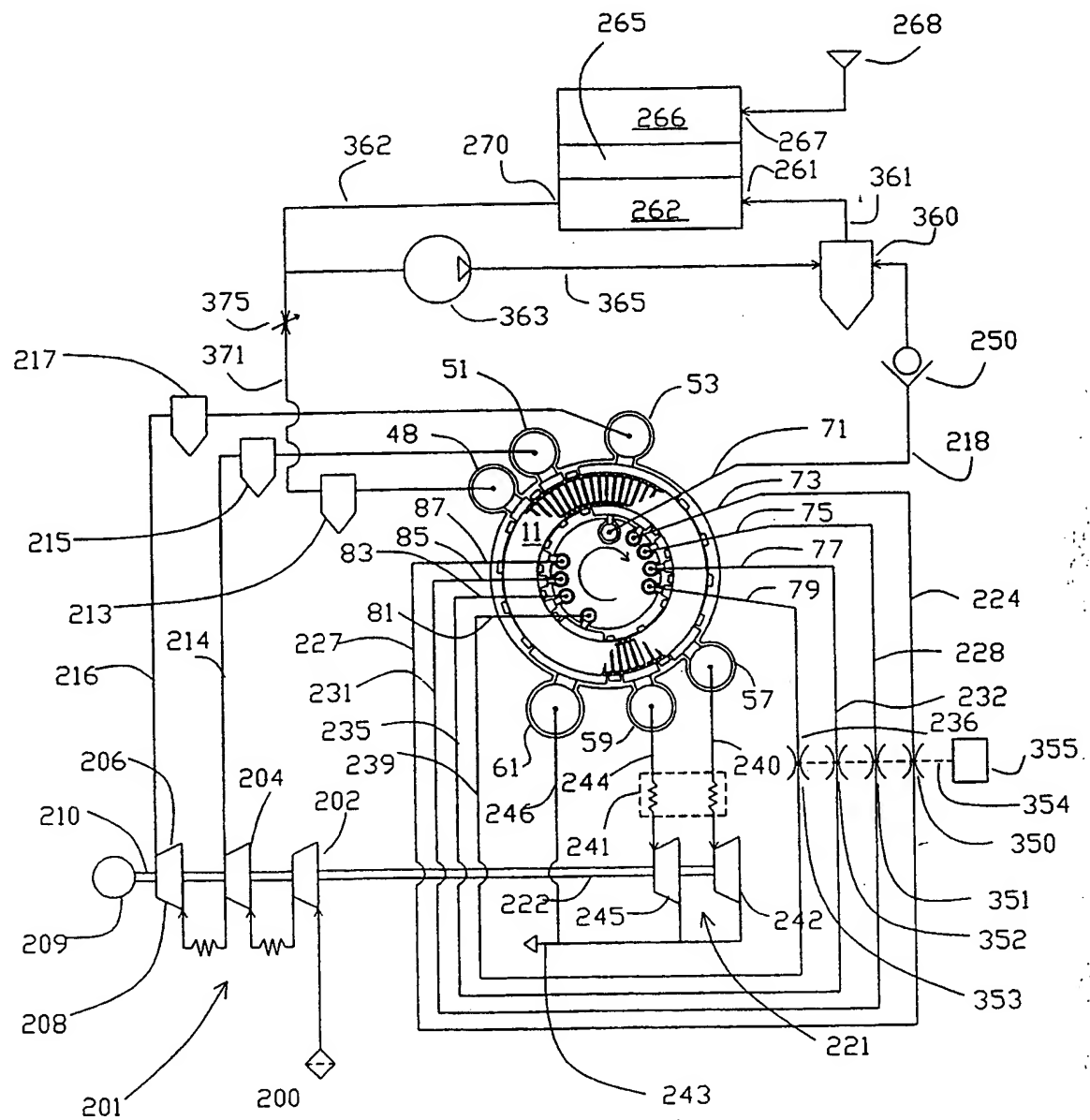


Fig.11

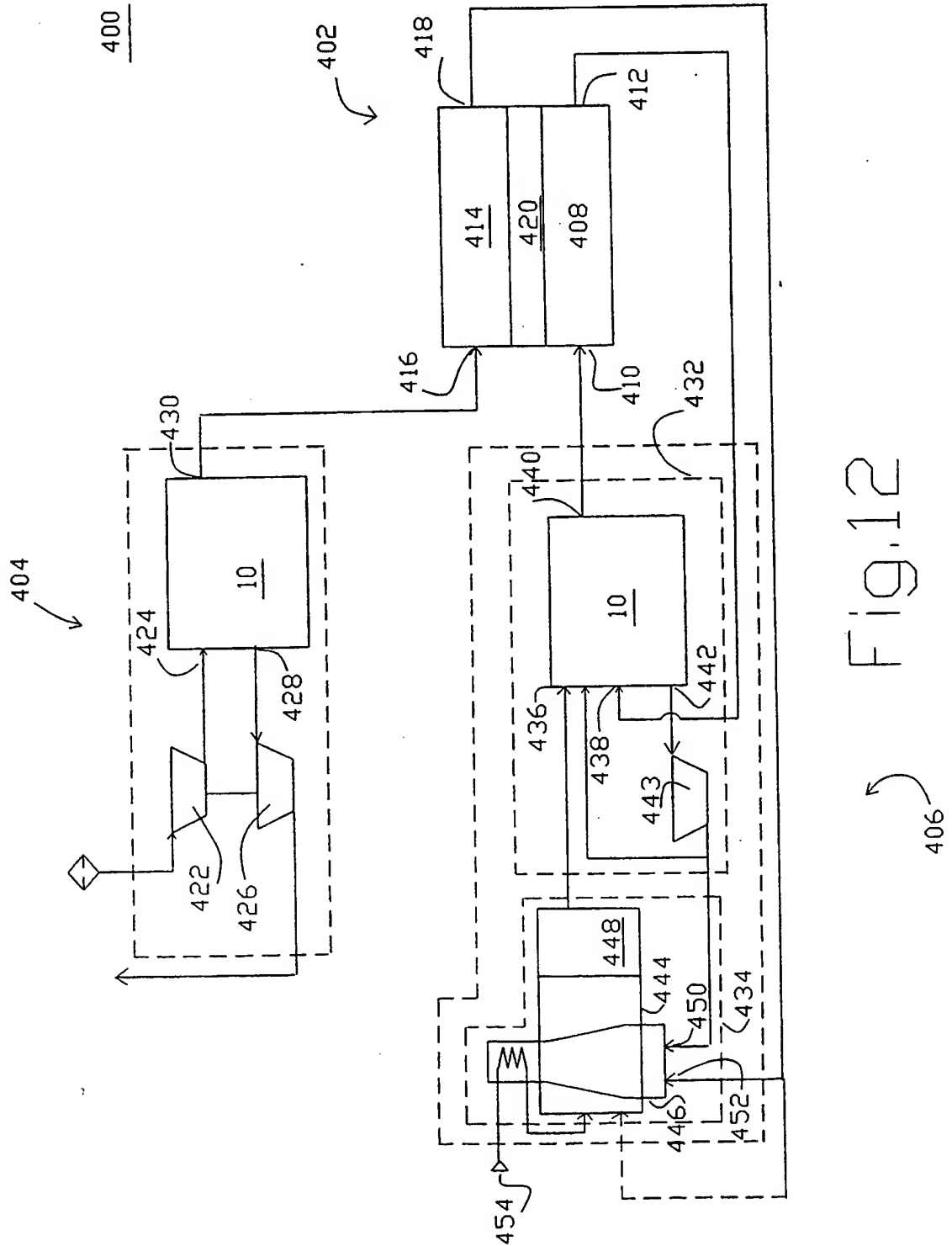


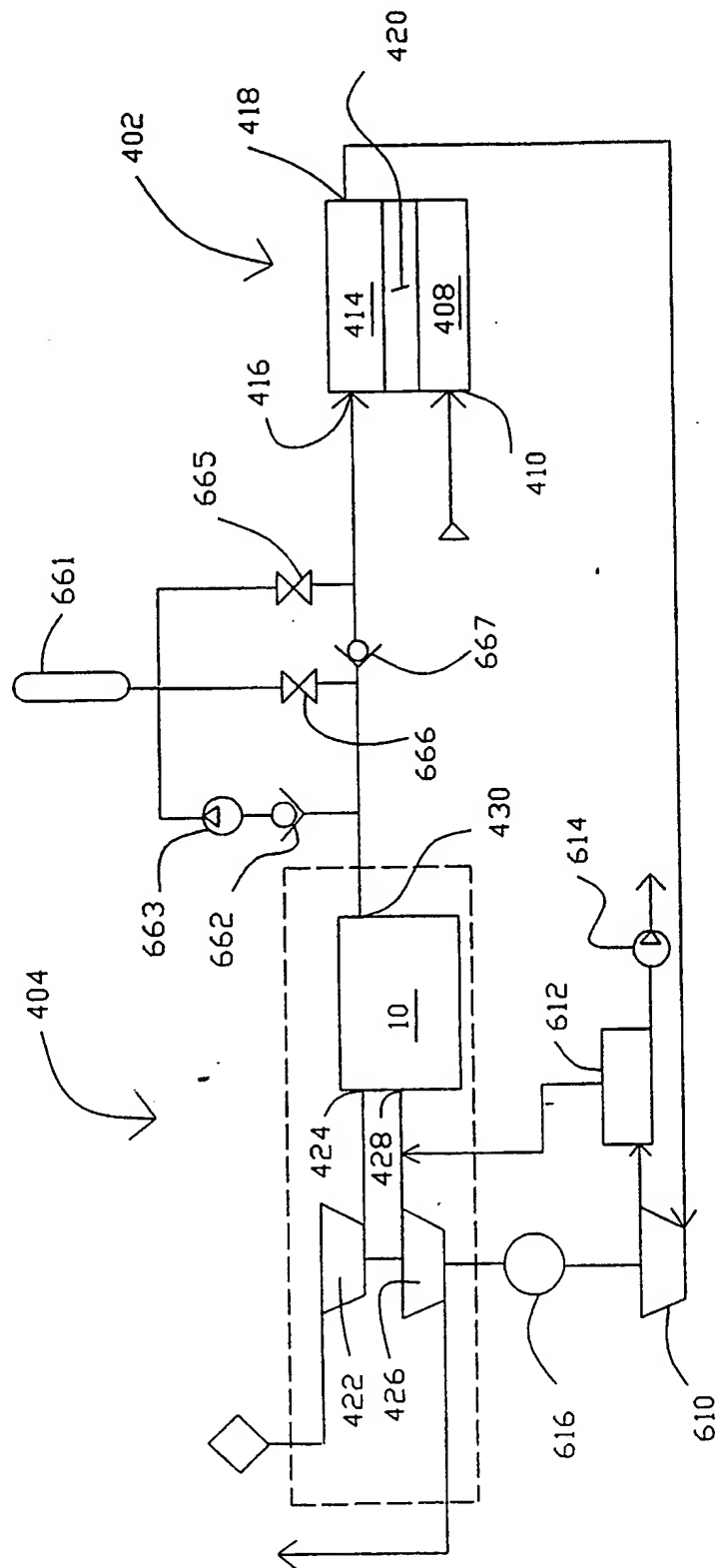
FIG. 12



506



Figure 14



**A. CLASSIFICATION OF SUBJECT MATTER**  
 IPC 7 H01M8/04

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

**\* Special categories of cited documents :**

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Date of the actual completion of the international search

11 February 2000

Date of mailing of the international search report

21/02/2000

Name and mailing address of the ISA

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Clement, J-P

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# INTERNATIONAL SEARCH REPORT

International Application No

PCT/CA 99/00823

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